LABORATORY OF PLASMA STUDIES

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Magnetically Insulated Diode

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Abstract

Local electron flux to the anode of a magnetically-insulated diode was monitored. Intense electron bursts to the anode and slow variations in the electron flux were observed. Unlike the slow signals the bursts were accompanied by sharp increases in microwave emission and by increases in the ion current density. The electron bursts were not affected by the presence of the anode plasma. Indications suggested that the bursts were initiated by processes in the cathode plasma.

I. Introduction

Although there has been considerable progress in the design of pulsed magnetically insulated diodes for the generation of intense ion beams,[1] the electron confinement and flow in such diodes is not well understood as yet. This flow not only largely determines the ion current density, by determining the effective accelerating gap,[2] but may also significantly affect the local fields in the diode gap, and thus the ion beam divergence. Since ideal one-dimensional equilibria[3-5] predict no electron crossing to the anode, it can be assumed that the electron convection to the anode results either from growing instabilities of the electron sheath,[6-7] from two-dimensional effects,[8] or from local nonuniformities in the diode.[8] Thus, the electron flow should be studied locally and compared to other local measurements.

In this study[9] we monitored the local electron flux to the anode through the 700 ns pulse of a ~100 kV magnetically insulated diode, by observing the electron bremsstrahlung emission. The electron flux showed short (~20 ns) intense bursts as well as slow (>100 ns) and usually smaller variations. The bursts occurred over an anode area of the order of 1 cm^2 and occured more often late in the pulse, when they carried a significant fraction of the electron current flowing to the anode. They were found to coincide in time with bursts in microwave emission and with short peaks in the ion current density. It is believed that processes in the cathode plasma lead to local perturbations in the electron flow which cause the burst occurrence. Unlike the short bursts, the slow changes in the electron flux to the anode were not found to be associated with microwave emission and were considerably reduced in the absence of anode plasma.

II. Experiments and Results

The magnetically insulated diode used, LONGSHOT,[10] has an annular accelerating gap with a radial insulating field, see Fig. 1(a). For the experiments described here, the anode was made of lucite with 1 mm diameter holes 5 mm apart, and the anode-cathode gap was 8-9 mm. The insulating field in the gap region was $\gtrsim$3 kG,[11] which is more than twice the critical field for magnetic insulation.[12] The pulse length was ~700 ns with the diode voltage and current waveforms as shown in Fig. 1(b).

A. Electron Flux Measurements

The relative electron flux to the anode was measured locally by monitoring the bremsstrahlung emission from the anode, using an x-ray collimator, pilot B scintillator, and a photomultiplier tube. The collimator looked perpendicular to the anode as shown in Fig. 1(b). Two such detectors were used in each experiment. The anode areas seen by the detectors were varied from less than 1 cm^2 to a few cm^2. When very small areas were observed, ~1 mm^2 tantalum bits were glued on the anode in order to enhance the bremsstrahlung emission. Emission of a few kilovolts was filtered out by the diode lucite flange.

The intensity of the bremsstrahlung changes over the pulse due to the gradually decreasing diode voltage. However, this did not affect the conclusions drawn here as will be shown. Also, the bremsstrahlung signal could be affected by changes in the incidence angles of the electrons on the anode. This effect was estimated for the case of tantalum on the anode. Due to electron scattering in the tantalum,[13] and because the bremsstrahlung observed was emitted at backward angles, a change in the incidence angle between 0° and 90° was estimated to affect the bremsstrahlung signal by only 10%.[14] Since the results were similar when the collimators viewed tantalum bits and Lucite we inferred that changes in the electron incidence angle had a negligible effect on the bremsstrahlung signal from the Lucite also.

The electron flux to the anode in a typical shot is shown in Fig. 2. Intense spikes of 10-30 ns duration are seen to be superimposed on a smaller, slowly increasing signal having a few tens to a few hundreds of ns duration, which generally rose in a few tens of nanoseconds. In each shot a few spikes could be observed with the average number being about 3. These spikes indicate intense electron bursts to the anode up to ten times the slowly varying signal of the electron flux.

The anode area over which electrons hit the anode could be estimated from shots in which two detectors viewed two neighboring portions of the anode. Figure 3(a) shows results of a shot in which the collimators viewed circular anode areas, 14 mm in diameter, with their centers separated by 20 mm. The upper trace shows a slowly rising signal and an intense burst. The slow variation does not occur in the other area (the lower trace). The lower trace shows two bursts the second of which coincides in time with the burst on the upper trace.

The fraction of the bursts which occurred simultaneously in both areas was determined. This fraction is plotted in Fig. 3(b) as a function of the distance between the viewed areas. Each point in the graph was obtained from more than 30 shots. From this graph it is inferred that most of the bursts are of a size ~1 cm. From the average number of bursts in a shot, and from our error in the time determination, we estimated that the fraction of bursts which could erroneously appear to be simultaneous is ~10%. Thus, the fraction of the bursts which appear to have a large spatial extent, $\gtrsim$20 mm, is actually less than the 20% shown in the graph. From these shots it could also be seen that on the average the slow variation of the electron flux occurred over somewhat larger anode areas than the electron bursts.

A few shots were carried out in order to test whether or not the bursts occurred at any particular radial position on the anode. We deduced that the bursts could occur at any point along the radial dimension of the anode.

The time distribution of the bursts is given in Fig. 4(a). It is seen that the bursts are much more frequent late in the pulse, occurring mostly between 300-600 ns after the beginning of the pulse. Figure 4(b) gives the distribution of the time interval Δt between two successive bursts, showing an average time interval of about 60 ns. In many shots the bursts were closely separated and appeared as a distinct group which lasted only about 100 ns.

The number of bursts present in the diode at each instant within the period of their most probable occurrence (between 300-600 ns, see Fig. 4(a)) can be estimated. Let us assume that in each shot 3 bursts of 20 ns duration occur, on the average, in each anode section of 1 cm in azimuth by 2 cm in radius. Thus, in each such section bursts occur over ~15% of this period. Since the anode perimeter is 60 cm long this means that at any instant during this period electron bursts to the anode occur, on the average, at ten different spots. Let us also assume that each burst occurs over an area of 1 cm^2 and that they increase the electron flux by an average factor of 5. Thus, the electron current which flows to the anode at each instant, over the area of the electron bursts (10 cm^2), is equal to the current which flows over 50 cm^2 of the anode with no electron bursts. Since the total anode area is 120 cm^2, this means that more than one third of the electron current to the anode is carried by the electron bursts.

Shots such as that in Fig. 3 were also used to examine whether the bursts move across the anode. Each group of shots, with a given distance between the viewed anode regions, was statistically analyzed in order to look for a systematic time shift between bursts occurring in the two regions. Except for the zero time-shift, where the correlation function clearly peaked, the values of this function were below the statistical noise (caused by the measurement error), so that no motion could be assigned to the bursts.

The current density in the electron bursts can be estimated if the total electron current flowing to the anode is known. Assuming that all the measured electron current flows to the lucite anode, the electron current of 30 kA at t = 400-500 ns gives an average current density of 250 A/cm^2 over the 120 cm^2 anode. Thus, the current density in the intense bursts can reach a value of ≥ 1 kA/cm^2. Assuming such a current density occurs over 1 cm^2 of the anode, then the magnetic field induced by the burst is at least 200 G. Such an induced field alters the magnetic field geometry in the diode. The local induced field can be assumed to be circular around the burst which causes the direction of the net magnetic field in the diode gap to deviate from the radial direction. This may cause a radial electron drift, thus leading to electron escape from the lucite anode region. The influence of the electron bursts on the diode operation may be especially significant since they occur mostly when the current density of the ion beam is high. (The ion current density was observed to be maximum in the second half of the pulse as will be described later in this paper.)

B. Microwave Emission from the Diode

Electron-sheath instabilities in the microwave frequency range may grow in crossed field devices.[6-7] It is also known[15] that the microwave radiation in magnetron devices grows with the increase of the electron current to the anode. In a magnetically insulated diode, it has been suggested that electron losses to the anode due to nonuniformities in the diode may be accompanied by RF emission.[8] Thus, the association of the observed electron bursts with microwave emission was examined. To this end it was decided to detect the microwave emission from as small a region of the diode as possible, since the electron bursts at the anode are local. Thus, a relatively high frequency antenna, ~53-70 GHz, was aimed towards the anode from a distance of 25 cm. This antenna viewed an anode section of ~7 cm length (as determined by the 3 db angle), but clearly it could detect microwaves from other parts of the diode due to reflections in the diode. The x-ray collimator was made to look at the same anode region. A microwave signal and the corresponding electron flux signal are shown in Fig. 5(a). A few spikes in the microwave signal appeared in each shot. A statistical analysis of 70 shots was carried out to examine the time correlation between the microwave and the electron bursts. The correlation was above the statistical noise only at zero time-shift where it had a statistically significant peak.

About one-third of the observed electron bursts coincided with microwave bursts and one-fifth of the microwave bursts coincided with electron bursts. Using the number of the bursts per shot and the time resolution of the measurements the probability for this to happen was calculated to be ~0.001. Thus, a considerable degree of simultaneity between the microwave and the electron bursts was shown. The number of the observed microwave bursts was larger than that of the electron bursts presumably since microwaves originating at regions of the diode, other than the region observed by the x-ray detector, could also be detected due to reflection in the diode. In Fig. 5(a) a rare example is shown where five microwave bursts are coincident with electron bursts. Figure 5(b) gives the time distribution of the microwave bursts which is very similar to that of the electron bursts (Fig. 4(a)), consistent with the coincidence found between the two kinds of bursts. The distribution of the time-intervals between microwave bursts was also very similar to that of the electron bursts.

The spikes in the microwave emission were almost always shorter than the electron bursts. They lasted from a few to ten nanoseconds while the electron burst duration was 10-30 ns. The microwave signal rose simultaneously with the sharp rise in the electron flux signal, but then decayed faster than the latter, as shown in Fig. 6(a). Slow increases in the electron flux were much less often accompanied by increases in the microwave emission as shown in Fig. 6(b), where microwave spikes were observed only with the sharply rising electron burst. The ratio between the amplitude of a spike in the microwave output and the amplitude of the signal before or after the spike was usually much larger (from a few to $\gtrsim$10 times larger) than the same ratio for the simultaneous electron burst. This shows that the slowly varying leakage of electrons to the anode contributes relatively little to the microwave emission. This result could not be affected by the fact that the antenna could detect microwaves from a larger region of the diode, since this could only increase the apparent quiescent microwave signal.

Ka-band (>26 GHz) microwaves were also detected, showing a spiky signal with the spikes again being shorter than the electron bursts. Simultaneity of the spikes with the electron bursts was not checked; however, the Ka-band signal in most cases was found to rise after a delay of ~250 ns and to fall between 500-600 ns, the period during which the electron bursts tended to occur (see Fig. 4(a)). Thus, it seems that the bursts in the Ka-band emission were also associated with the electron bursts. Note that both detected microwave frequency bands are higher than the electron cyclotron frequency, which is ~5 GHz.

C. Effect of Anode Plasma on the Electron Flux

In order to examine the effect of the anode plasma or the ions on the electron flux to the anode, we performed experiments with silver painted anodes, where the anode flashover was inhibited due to the high conductivity of the anode surface. Measurements of the ion current density by the use of a scintillator (see Sec. D) verified that the ion current density was reduced by at least a factor of 30. Examples of the electron flux in such shots are given in Fig. 7. Electron bursts are observed, with their shape being similar to that observed with ions and anode plasma. However, the slowly varying electron leakage to the anode is much smaller in the absence of the anode plasma.

These results show that the contribution of the ions in the diode gap and of the anode plasma to the formation of the electron bursts is minor. This leads to the conclusion that time-dependent processes in the electron sheath or in the cathode plasma cause the bursts. However, the relatively long and slowly rising increases in the electron flux are strongly affected by the presence of the ions and the anode plasma. This is being investigated and will be described in a publication to follow.[16]

D. Ion-Flux Measurements

The electron and the ion space charges in the diode gap are balanced to a large extent, since otherwise electric fields, larger than the applied field, will be produced. Therefore, changes in the ion current density in the diode imply changes in the total electron population across the gap. Thus, in order to study the fluctuations of the charge in the gap, which are associated with the electron bursts, we measured the relative ion current density from the same diode region where the electron flux was measured. Ions were passed through a few millimeter diameter aperture located about 6 cm from the anode, see Fig. 1(a). They impinged on a pilot B scintillator sheet the light from which was monitored by a photomultiplier tube. Ions emitted from an anode area $\lesssim$1 cm in diameter could be detected. The intensity of the light from the scintillator could be made to increase by increasing the aperture diameter or by decreasing the aperture-scinillator distance. Such tests verified that the scintillator responded almost linearly so that the tube signal was nearly proportional to the ion current. Many electron bursts were found to be accompanied by short peaks in the local ion current density, as shown by the example in Fig. 8. (This was not observed when the electron flux and the ion detectors looked at different diode regions, several centimeters apart.) We do not yet know whether the peaks in the ion current density resulted from an increased ionization of the anode plasma (this can increase the ion current density if the latter is limited by the plasma ion density, i.e., source limited). However, the increase in the ion current density at least shows that the electron bursts to the anode are accompanied by an increase in the local total electron population across the gap. These charge fluctuations are believed to result in fluctuating electric fields which affect the ion trajectories, and thus the ion beam divergence, as will be discussed in the following paper.[16]

We note that our relative ion current density measurements agree in the overall shape with those previously made using a Rogowski belt,[17] i.e., both measurements show that the ion current density rises after a delay of 200-300 ns with respect to the start of the voltage pulse. However, the present measurements with the scintillator sheet and photomultiplier revealed fast (a few nanoseconds) and slow temporal variations of the ion current density. These variations were observed even when the measurement was an average over an anode section of ~20 mm length and 24 mm width. Many sudden increases in the ion current density which were not simultaneous with a change in the electron flux were also observed. Also, many changes in the electron flux could not be consistently correlated to changes in the ion current density. The analysis of these observations is continuing, including new observations correlating electron flux and ion beam divergence. This will also be discussed in the next publication.[16]

Summary and Discussion

The electron flux at the anode of the LONGSHOT magnetically-insulated-diode was studied locally. Short intense electron bursts occurred both with and without an anode plasma formed in the diode while the slowly rising variations appeared only with anode plasma. The size of the anode involved in an electron burst varied between a few millimeters and a few centimeters, but 1 cm was typical. The bursts were more frequent in the second half of the pulse therefore they could significantly affect the ion beam generation since most of the ions were extracted during this period. It is estimated that ten bursts occur in the diode at each instant during the second half of the pulse, carrying a considerable fraction of the electron current which flows to the anode. The bursts probably induce magnetic fields large enough to alter the direction of the net magnetic field in the gap, thus causing an electron drift in the radial direction, and consequently reducing the actual electron residence time in the gap.

The electron bursts were found to be unaffected by the presence or the absence of the anode plasma. Also, unlike the slowly rising electron flux to the anode, they were accompanied by short bursts of microwave emission. It is not clear yet whether the electron bursts are caused by fluctuating fields due to growing instabilities of the electron sheath or by nonuniformities introduced by the cathode plasma. However, since the time separation between the bursts (a few tens of nanoseconds) is much longer than the electron time scale, and because the bursts are stationary within a region of 1-2 cm in size for a period of 10-30 ns (again long compared to the electron motion time scale) we believe that processes in the cathode plasma initiate the formation of the electron bursts, i.e., that time-dependent nonuniformities in the cathode plasma affect the electron flow in the diode gap. The large time-separation between the bursts can be explained by assuming that the perturbations in the cathode plasma occur only under certain conditions of this plasma. The fact that sometimes the bursts in a shot were grouped together, occurring during a relatively short period, is also consistent with this assumption. We note that even if electron sheath instabilities are responsible for the formation of the bursts, the growth of these instabilities very probably depends on the time-dependent local boundary conditions, determined by the cathode plasma. This is assumed in order to allow for the localization of the bursts and for their large time-separation.

The electron bursts were found to cause step increases in the local ion emission from the diode, which indicates changes in the total positive (and therefore the negative) charge within the gap. Such charge fluctuations associated with the electron bursts may cause strong transverse electric fields in the diode which could significantly affect the ion beam divergence. This effect was observed and will be reported in a separate study,[16] in which the relation between the slow changes in the electron flux and the transverse electric fields in the diode will also be discussed.

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Figure Captions

Fig. 1 a) Schematic diagram of the LONGSHOT diode and the measurement system. The anode annulus is with 17.8 cm i.d. and 22 cm o.d. The hollow cathode is a ring 22 cm in diameter. The insulating magnetic field is produced by two coils. The x-ray collimator view of the anode was through the lucite flange, and was almost perpendicular to the anode. The microwave horn had a similar view of the accelerating gap region. The local ion current density was measured by the use of an ion aperture, a scintillator sheet, and a photomultiplier (PM) tube.

b) Typical voltage and current waveforms.

Fig. 2 Typical bremsstrahlung signal (negative) measured by a detector which viewed an anode area of 15 mm diameter. The voltage pulse starts at the arrow and the dashed line at the left indicates the base line.

Fig. 3 a) Signals (negative) from two bremsstrahlung detectors, each viewing an anode area of 14 mm diameter. The distance between the centers of the areas was 20 mm. The lower trace is displaced on the oscilloscope screen. The fiducial marks are indicated by the solid arrows and the beginning of the pulse in the upper trace is indicated by the dashed arrow. The dashed lines at the left indicate the baselines.

b) Fraction of electron bursts simultaneously observed by both detectors as a function of the distance d between the viewed areas. The viewed areas were made smaller for smaller d to avoid an overlap between the areas. The line indicates the trend.

Fig. 4 a) Number of bursts occurring during a time interval of 40 ns as a function of time t. t = 0 marks the start of the voltage pulse.

b) Number of pairs of successive electron bursts separated by a time interval $\Delta t \pm 5$ ns as a function of Δt. The lines indicate the trend.

Fig. 5 a) Upper trace: electron flux signal (negative) measured by a detector which viewed an anode section of 7 cm length. Lower trace: microwave emission ($50 < \omega < 70$ GHz) signal (positive) detected by an antenna viewing the same diode region. The fiducial marks (arrows) indicate t = 650 ns with respect to the beginning of the pulse. The five spikes in both signals are coincident to within the measurement accuracy (±5 ns). (The electron bursts appear ~140 ns after the microwave bursts because of an instrumental delay caused by the PM tube and the cables).

b) Number of bursts in microwave emission occurring during a time interval of 40 ns vs. time. t = 0 marks the start of the pulse. The line indicates the trend.

Fig. 6 a) Electron flux (upper trace) and microwave emission (lower trace). The fiducial marks, at the end of each sweep, indicate t = 660 ns after the start of the pulse. The short high spike in the microwave emission coincides with the sharp rise in the electron flux (both are marked with arrows). (The electron burst appears in the picture after the microwave burst due to an instrumental delay as in Fig. 5(a).)

b) The electron burst (solid arrow in the upper trace) and the sharp increase in the electron flux (dashed arrow) are associated with microwave bursts which are indicated by the solid and dashed arrows, respectively, in lower trace. (The microwave burst marked with the dashed arrow is barely visible.) The slow change in the electron flux, within about 100 ns near the dashed arrow, is not accompanied with microwave emission.

Fig. 7 Bremsstrahlung signals recorded in two shots with a silver painted anode. The upper trace (negative) was obtained with a detector viewing an anode area of 15 mm diameter. The lower trace (positive) corresponds to an anode region of 15 mm in the radial and 30 mm in the azimuthal direction. The beginning of the pulse and the fiducial marks are indicated by the left and the right arrows, respectively. The dashed lines at the left indicate the baselines.

Fig. 8 Upper trace: Bremsstrahlung signal (negative) measured by a detector viewing an anode area of 12 mm diameter. Lower trace: light intensity signal (positive) produced by ions passing through an aperture, 2 mm in diameter, and hitting a scintillator sheet. The anode-aperture distance was 73 mm. In each trace the solid and the dashed arrows indicate the start of the pulse and the fiducial mark, respectively. The time base is 100 ns/div.

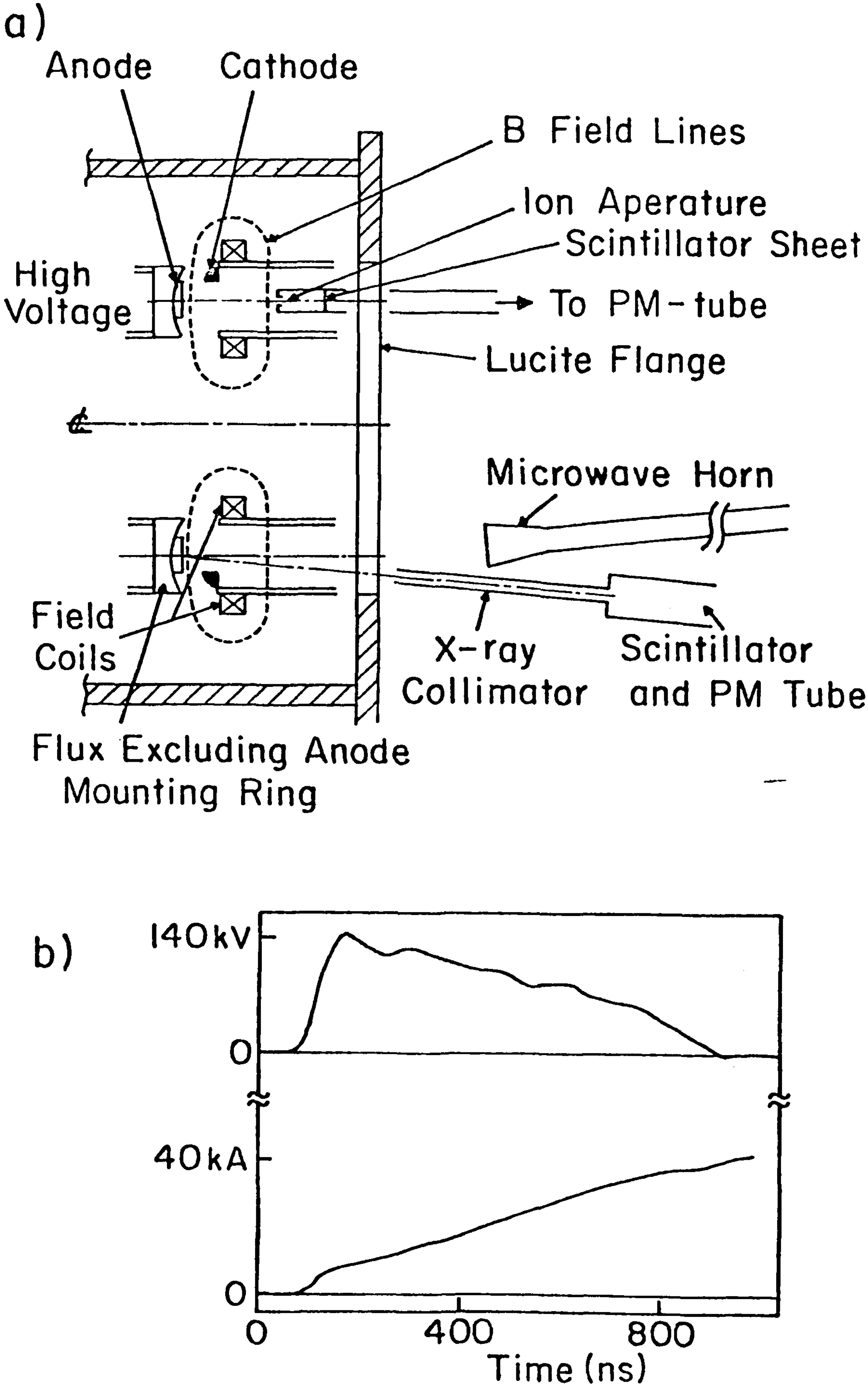
a)
Anode
Cathode
B Field Lines
Ion Aperature
Scintillator Sheet
High Voltage
To PM-tube
Lucite Flange
Microwave Horn
Field Coils
X-ray Collimator
Scintillator and PM Tube
Flux Excluding Anode Mounting Ring
b)
140kV
0
40kA
0
0
400
800
Time (ns)

Figure 1

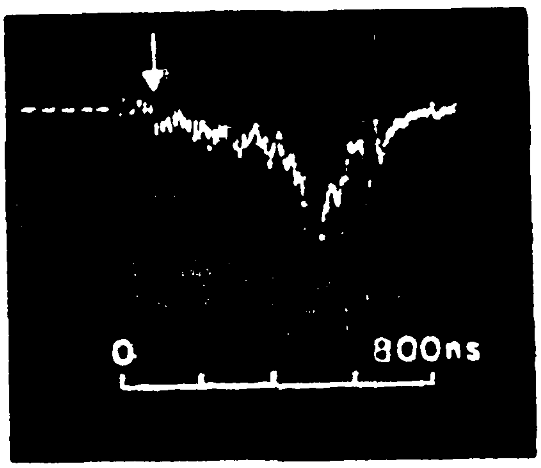

Figure 2

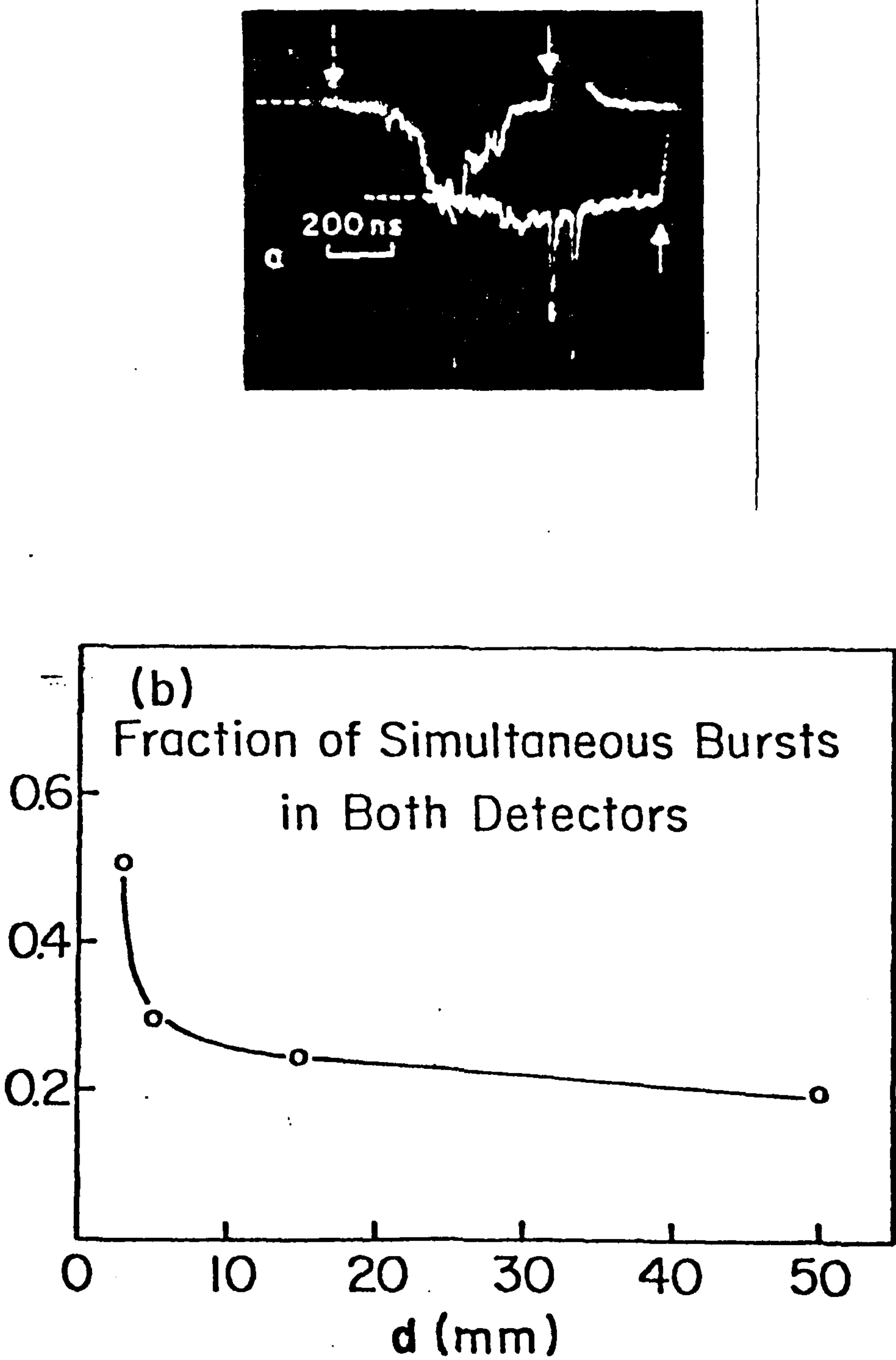
200ns
a
(b)
Fraction of Simultaneous Bursts
in Both Detectors
0.6
0.4
0.2
0
10
20
30
40
50
d (mm)

Figure 3

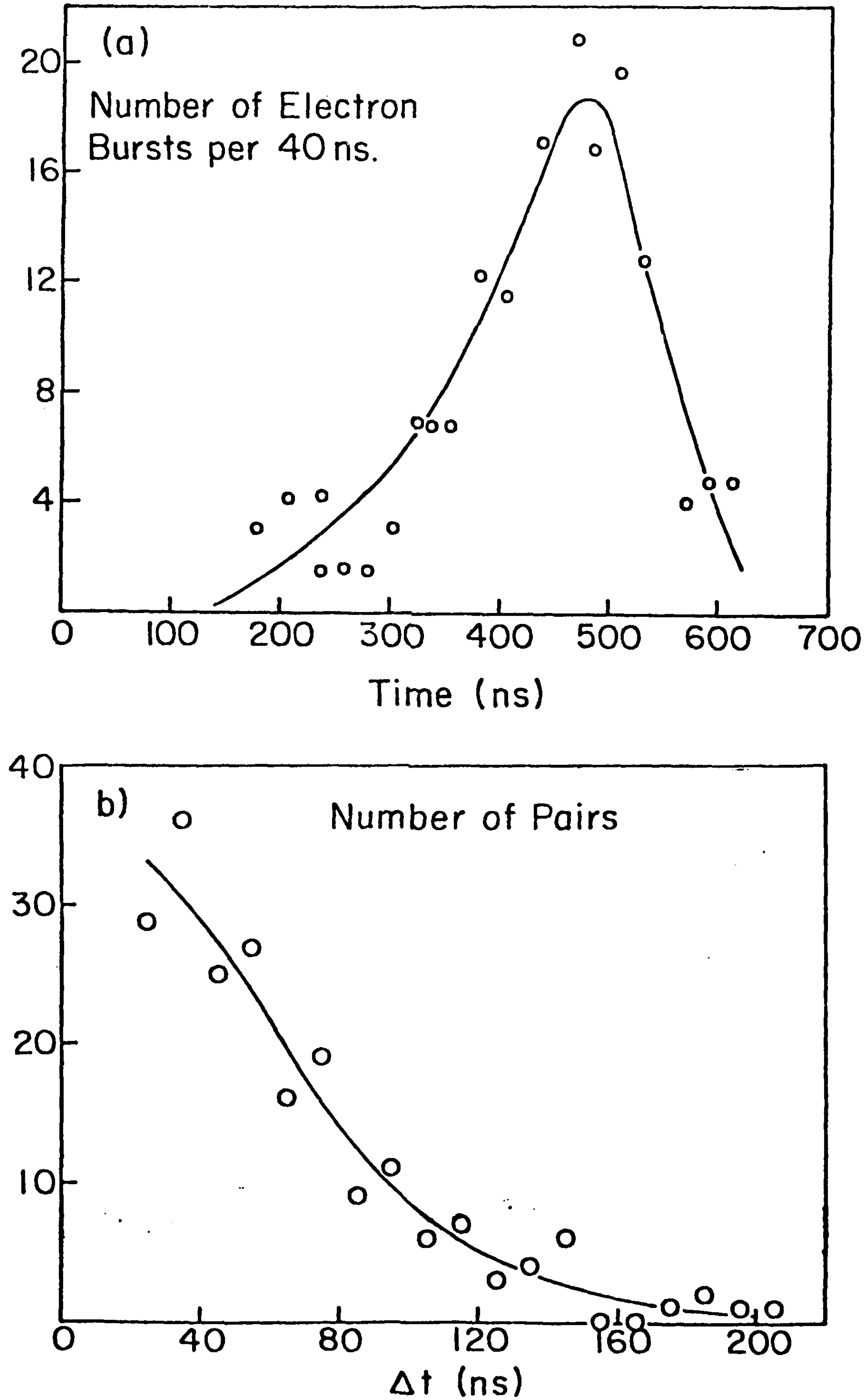
(a)
Number of Electron
Bursts per 40 ns.
20
16
12
8
4
0
100
200
300
400
500
600
700
Time (ns)
40
b)
Number of Pairs
30
20
10
0
40
80
120
160
200
Δt (ns)

Figure 4

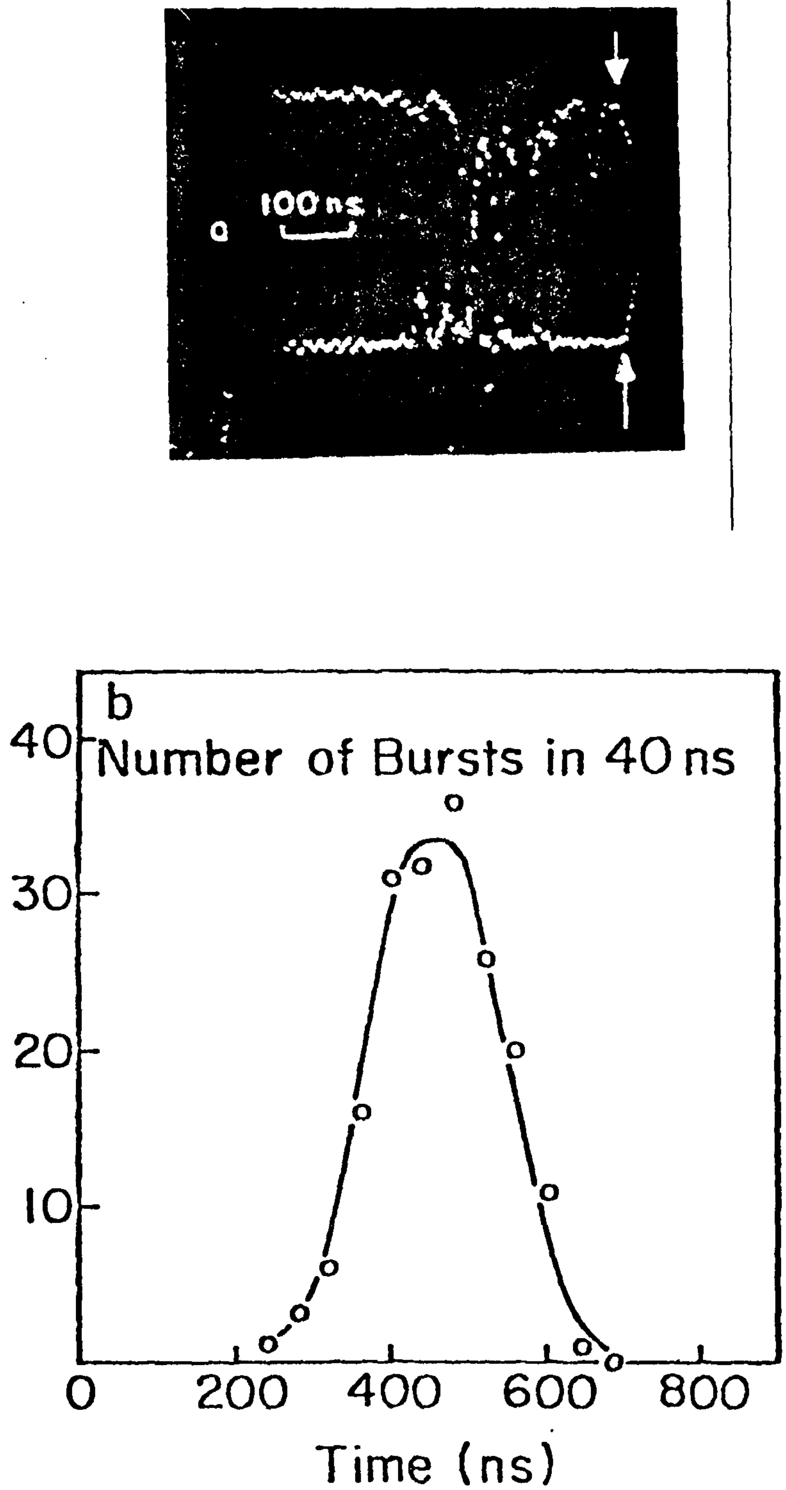
a
100 ns
b
Number of Bursts in 40 ns
0
10
20
30
40
200
400
600
800
Time (ns)

Figure 5

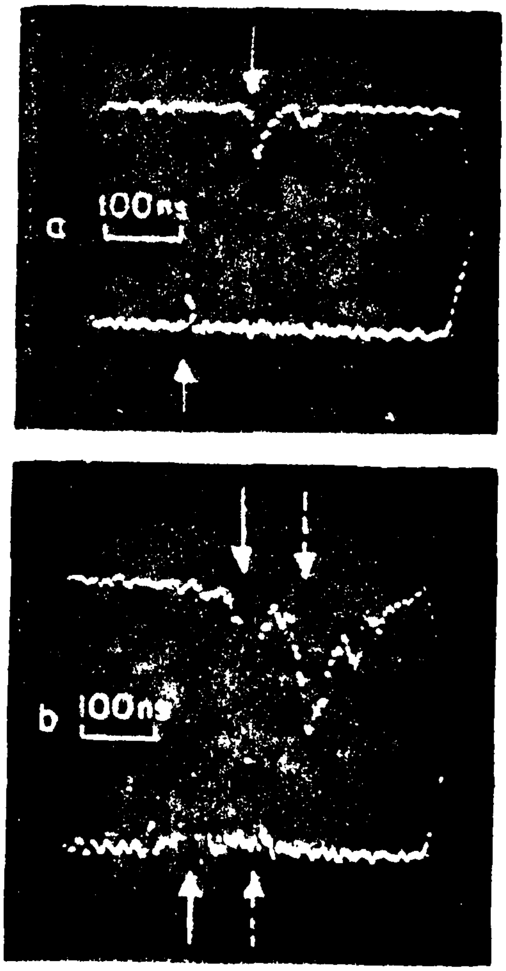

Figure 6

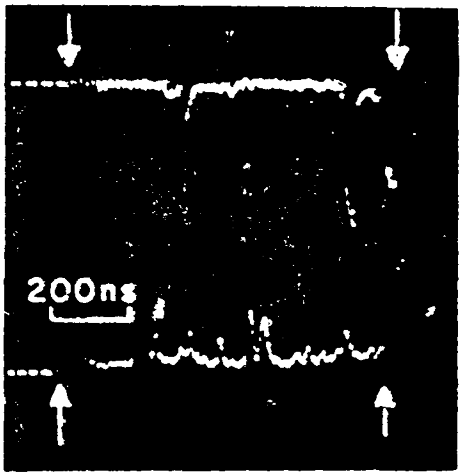

Figure 7

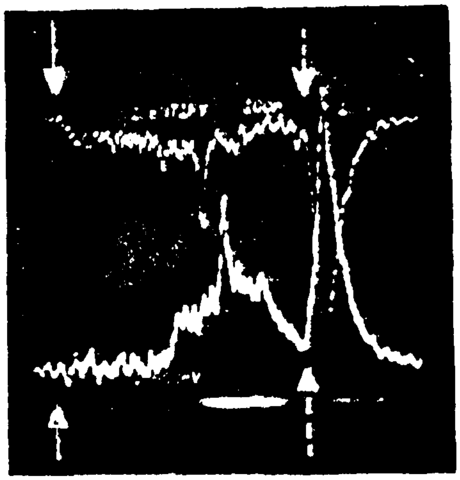

Figure 8